TITLE OF THE INVENTION

LIQUID CRYSTAL THERMO-OPTIC SWITCH AND ELEMENT

CROSS-REFERENCE TO RELATE APPLICATIONS

(Not applicable)

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

(Not Applicable)

REFERENCE TO "SEQENCE LISTING," A TABLE, OR COMPUTER PROGRAM LISTING APPENDIX SUBMITTED ON A COMPACT DISC

(Not Applicable)

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates generally to optical switches of the integrated optic type, and more particularly to a liquid crystal based thermo-optic switch capable of redirecting optical beams of arbitrary polarization state in a channel waveguide geometry. Additionally, the invention relates to an integrated optic variable attenuator based on this switch architecture.

2. Description of the Related Art

[0002] Currently, a typical integrated optic switch employs either electro-optic [see for example R.C. Alferness, "Guided Wave Devices for Optical Communication", IEEE J. Quantum Electron., vol. QE-17, pp. 946-958 (1981); U.S. Patent Nos. 4,070,092 and 4,775,207] or thermo-optic [see for example B.A. Moller, L. Jensen, C. Laurent-Lund, and C. Thirstrup, "Silica Waveguide Thermo-Optic Phase Shifter with Low Power Consumption and Low Lateral Heat

Diffusion", IEEE Photonics Technol. Lett., vol. 5, pp. 1415-1418 (1993); U.S. Patent Nos. 6,084,050 and 6,311,004] effects to produce differential refractive index loading between two optical pathways within the switch which in turn directs the guided optical mode into a particular output pathway, usually the higher loaded pathway. The refractive index loading produced by electro-optic effects is inherently birefringent in that these materials load the two polarization states of the guided mode(s) differently which complicates the switch design. Thermo-optic loading can be polarization independent but the magnitude of the effect in currently available thermo-optic materials is limited requiring high differential temperatures to induce complete switching. Liquid crystal based optical switches [see for example R.A. Soref, "Liquid-Crystal Fiber-Optic Switch", Opt. Lett., vol. 4, pp. 155-157 (1979); M. Kobayashi et al., "2x2 Optical Waveguide Matrix Switch Using Nematic Liquid Crystal", IEEE J. Quantum Electron., vol. QE-18, pp. 1603-1610 (1982); U.S. Patent No. 4,828,362] benefit from the large refractive index loading provided by the liquid crystal reorientation but are also sensitive to the polarization state of the optical radiation being switched. Due to these limitations, current integrated optic switches can be difficult to implement.

BRIEF SUMMARY OF THE INVENTION

[0003] According to one aspect of the invention, an integrated optic switch is provided, the switch including an optical Y-branch waveguide structure capable of guiding at least one optical mode. The structure includes a cladding medium, a channel waveguide core disposed in said cladding medium and containing an input branch and first and second output branches, a first liquid crystal material, and first temperature control element in heat exchange relationship with the first liquid material. The first liquid crystal material is associated with the first output branch and has ordinary and isotropic refractive indices corresponding to nematic and isotropic phases of the liquid crystal material, respectively. The first temperature control element selectively adds heat to the first liquid crystal material to thereby change the phase thereof from nematic to isotropic, said change producing

differential refractive index loading of the optical Y-branch waveguide such that at least a portion of optical mode light directed into one of the first and second output branches is redirected into the other of the first and second output branches.

[0004] According to a further aspect of the invention, a variable optic attenuator is provided, including a cladding medium, a channel waveguide core disposed in said cladding medium and capable of guiding at least one optical mode, the channel waveguide core containing at least one input branch and at least first and second output branches, a first liquid crystal material associated with the first output branch and having ordinary and isotropic refractive indices corresponding to nematic and isotropic phases of the liquid crystal material, respectively, and one or more temperature control elements disposed in heat exchange relationship with the first liquid crystal material, each temperature control element selectively adding heat to a corresponding portion of the first liquid crystal material to thereby change the phase thereof from nematic to isotropic, the change producing differential refractive index loading of the channel waveguide core such that at least a portion of optical mode light directed into one of the first and second output branches is redirected into the other of the first and second output branches.

[0005] According to a further aspect of the invention, a liquid crystal thermo-optic element capable of being held in either of two polarization independent refractive index states is provided. The element includes a solid medium capable of transmitting optical radiation propagating along a given direction, and a liquid crystal material having ordinary and isotropic refractive indices corresponding, respectively, to nematic and isotropic phases, wherein, in the nematic phase, a first index of refraction is presented to optical radiation in the solid medium, and in the isotropic phase, a second index of refraction is presented to optical radiation in the solid medium. The element further includes a temperature control element disposed in heat exchange relationship with the liquid crystal material, the temperature control element selectively causing switching in the liquid crystal material between one and the other of the nematic and isotropic phases.

[0006] According to a further aspect of the invention, a method is provided for selectively directing light in an input branch of an optical structure into one or more of multiple output branches, at least one of said output branches having associated therewith a liquid crystal material having ordinary and isotropic refractive indices corresponding, respectively, to nematic and isotropic phases, the liquid crystal material having a temperature control element in heat exchange relationship therewith. The method includes launching light into the optical structure, and using the temperature control element to change the phase of the liquid crystal material from one to the other of the nematic and isotropic phases, thereby causing at least a portion of the light launched into the optical structure to be redirected from one output branch into another.

[0007] In accordance with an aspect of the invention, the liquid crystal material is chosen to have positive birefringence so that its ordinary refractive index, when the material is in its nematic phase, is less than its isotropic refractive index. For the switch to operate, the two trenches are held at different temperatures: one trench is held at a temperature a few degrees below the liquid crystal clearing temperature and the other trench is held at a temperature a few degrees above the clearing temperature. When a given trench is held at the lower temperature, the liquid crystal is in its nematic phase with its director aligned along the long direction of the trench so that both polarizations of the guided mode are loaded by the liquid crystal's ordinary refractive index. When the other trench is held at the higher temperature, the liquid crystal is in its isotropic phase and therefore both polarizations of the optical mode experience an increased level of loading due to the liquid crystal's isotropic index. The lengths of the trenches and their proximity to the channel waveguide core are chosen so that the differential refractive index loading on the Y-branch is sufficient to cause the guided mode to be completely switched into the path loaded by the liquid crystal's isotropic index. Since the differential loading on the Y-branch produced by this combination of liquid crystal nematic orientation and choice of liquid crystal phases employed is polarization independent, the switch is polarization independent.

[0008] Also according to this invention, a variable optical attenuator is formed by providing means to control the temperature within one or both of the trenches over a plurality of sections. The length of each trench section is chosen to be a fraction of that needed to produce complete switching. By creating differential loading of the channel waveguide Y-branch at only a subset of the sections, only a portion of the guided mode is switched. One of the two output paths from the switch can therefore be used to provide the attenuated beam while the second path provides the compliment beam.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0009] Many advantages of the present invention will be apparent to those skilled in the art with a reading of this specification in conjunction with the attached drawings, wherein like reference numerals are applied to like elements, and wherein:

[0010] FIG. 1 is a perspective view illustrating a liquid crystal thermo-optic integrated optic switch in accordance with the present invention showing a channel waveguide Y-branch, two liquid crystal filled trenches, and propagation directions of input and output optical modes for a case in which it is the lower trench that is held above the liquid crystal clearing temperature.

[0011] FIG. 2 is a cross-sectional view of a liquid crystal thermo-optic integrated optic switch taken along the line 2-2 of FIG. 1 and showing the channel waveguide structure including the Y-branch core and the two liquid crystal filled trenches, and the two temperature control elements.

[0012] FIG. 3 is a cross-sectional view of an alternate liquid crystal thermo-optic integrated optic switch geometry showing alternate positions for the temperature control elements, and a superstrate that is bonded to the waveguide structure and which seals the liquid crystal filled trenches.

[0013] FIG. 4 is a perspective view of an alternate liquid crystal thermo-optic integrated optic switch architecture showing the channel waveguide Y-branch, a single liquid crystal filled trench, a second trench filled with a fixed index material,

and the propagation directions of the input and output optical modes for the case in which the trench is held below the liquid crystal clearing temperature.

[0014] FIG. 5 is a cross-sectional view of another alternate liquid crystal thermo-optic integrated optic switch architecture showing the channel waveguide structure including the Y-branch core and two shallow liquid crystal filled trenches, and two temperature control elements.

[0015] FIG. 6 is a top view of an alternate embodiment of the liquid crystal thermo-optic integrated optic switch in which the switch is configured to operate as a variable attenuator showing the channel waveguide Y-branch, the two liquid crystal filled trenches, the segmented temperature control elements, and the propagation directions of the input and two output optical modes for the case in which most of the sections of the upper trench are held above the clearing point while most of the sections of the lower trench are held below the clearing point.

[0016] FIG. 7 is a top view of an alternate embodiment of the liquid crystal thermo-optic variable attenuator, showing the single channel waveguide, the single liquid crystal filled trench, the segmented temperature control elements, the input optical mode, the radiated optical energy, and the attenuated output optical mode for the case in which most of the sections of the trench are held above the clearing point.

[0017] FIG. 8 is a top view illustrating an alternate liquid crystal thermo-optic integrated optic switch geometry showing the Mach-Zehnder waveguide structure, the two liquid crystal filled trenches, and the propagation directions of the input and output optical modes for the case in which the switch is in the cross state.

DETAILED DESCRIPTION OF THE INVENTION

[0018] A perspective view of the liquid crystal thermo-optic switch **10** is shown in FIG. 1. For clarity, a cross-sectional view of the thermo-optic switch taken along the line 2-2 in FIG. 1 is shown in FIG. 2. The switch is comprised of a channel waveguide Y-branch **11** embedded within a surrounding cladding medium **12**, two trenches **13** filled with a liquid crystal material **14**, and two temperature control

elements **15** (see FIG. 2). Each temperature control element **15** maintains the temperature of the liquid crystal material **14** in its associated trench **13** at one of two temperatures, one temperature a few degrees above the liquid crystal material's clearing temperature and the alternate temperature a few degrees below the clearing temperature. When the liquid crystal material **14** in a given trench **13** is held at the lower temperature, the liquid crystal material **14** is well into its nematic phase. When in the nematic phase, the nematic director within the volume of the liquid crystal **14** is made to align with the long dimension of the trench **13** by steric and/or surface alignment forces at the inner surfaces of the trench **13**. In FIG. 1, the liquid crystal material **14a** in the upper trench **13a** is depicted as being in its nematic phase. Since the trenches **13** are substantially parallel to the propagation direction of the optical mode(s) **16** guided within the Y-branch **11**, the portion of the evanescent field of the mode(s) **17a** that reaches the nematic liquid crystal material **14a** propagates along the nematic director so that both polarizations of the evanescent field **17a** encounter the same ordinary refractive index of the liquid crystal material **14a**. When the liquid crystal material **14** in a given trench **13** is held at the higher temperature, the liquid crystal material **14** is well into its isotropic phase. In FIG. 1, the liquid crystal material **14b** in the lower trench **13b** is depicted as being in its isotropic phase. Since the isotropic index is polarization independent, both polarizations of the portion of the evanescent field of the mode(s) **17b** that reach the isotropic liquid crystal material **14b** within the lower trench **13b** encounter the same isotropic refractive index of the liquid crystal material **14b.**

[0019] The liquid crystal material **14** is chosen to have positive birefringence so that the isotropic refractive index is higher than the ordinary refractive index. Moreover, the Y-branch **11** and liquid crystal materials **14** are also chosen so that the liquid crystal material's **14** isotropic refractive index is lower than the Y-branch material's **11** refractive index. This choice of indices allows the effective index of the Y-branch **11** to be loaded by the refractive indices of the liquid crystal filled trenches **13** when the liquid crystal material **14** is in either the nematic or isotropic phase without causing the guided mode **16** to radiate from the Y-branch **11**. The

refractive index loading of the Y-branch **11** is higher when the liquid crystal material **14** is in its isotropic (higher index) phase than when the liquid crystal material **14** is in its nematic (lower index) phase.

[0020] The switch is operated by holding the liquid crystal material **14a/b** in one trench **13a/b** at the lower temperature while holding the liquid crystal material **14b/a** in the other trench **13b/a** at the higher temperature so as to produce differential refractive index loading of the Y-branch **11**. The length of the trenches **13**, as well as the lateral distance **18** between the trenches **13** and the Y-branch **11**, are chosen in conjunction with the individual levels of refractive index loading to provide a sufficient differential loading of the Y-branch **11** to direct the guided mode **16** into the output arm **19b/a** of the Y-branch **11** that is adjacent to the trench **13b/a** containing the isotropic liquid crystal material **14b/a**.

[0021] As shown in FIG. 2, when held at the lower operating temperature by a temperature control element **15**, the nematic liquid crystal material **14** can be aligned within the trench **13** through the use of alignment coatings **31** deposited on the trench walls **32**, or on the trench floor **33**, or on the trench ceiling **34**, or on a combination of these surfaces. The alignment coatings **31** can be deposited, for example, by the oblique evaporation of SiO, M. Monkade, Ph. Martinot-Lagarde, G. Durand, and C. Granjean, "SiO Evaporated Films Topography and Nematic Liquid Crystal Orientation", J. Phys. II France, vol. 7, pp. 1577-1596 (1997). For the case in which just the trench walls **32a,b,c,d** are coated, only two oblique evaporations are needed: one from the right to coat the left walls **32a,c** and the other from the left to coat the right walls **32b,d**. The aspect ratio of the trenches **13** is chosen to avoid shadow effects during the deposition of the alignment coatings **31**. In FIG. 2, the liquid crystal material **14a** in the left trench **13a** is depicted as being in its nematic phase with the liquid crystal director aligned in the direction normal to the page. At the higher operating temperature, the alignment coatings have little or no effect on the liquid crystal material **14**. In FIG. 2, the liquid crystal material **14b** within the entire volume of the trench **13b** is depicted as being in its isotropic phase.

[0022] Although in the foregoing discussion the temperature control elements **15** were shown to be embedded within the cladding medium **12** and positioned on top of the trenches **13** (see FIG. 2), the temperature control elements **15** could be positioned at other locations in the proximity of the trenches **13**. As shown in FIG. 3, the liquid crystal thermo-optic switch **40** could be configured with the temperature control elements positioned laterally from or below the trenches **13** as suggested by the dashed lines **15'**. For such alternate temperature control element positions, a superstrate **41** could be bonded to the top surface of the switch **42** by, for example, a modified anodic bonding process, J.M. Ruano, V. Benoit, J.S. Aitchison, and J.M. Cooper, "Flame Hydrolysis Deposition of Glass on Silicon for the Integration of Optical and Microfluidic Devices", Anal. Chem., vol. 72, pp. 1093-1097 (2000). The superstrate **41** serves the dual function of providing a surface on which an alignment coating **31** could be deposited while also covering and sealing the trenches **13**.

[0023] Whereas in the foregoing discussion the trenches **13** were filled with a liquid crystal material **14** having positive birefringence, the trenches **13** could alternatively be filled with a liquid crystal material having negative birefringence. In this case, the differential refractive index loading of the Y-branch **11** would result in the guided mode **16** being directed into the output arm **19a/b** of the Y-branch **11** that is adjacent to the trench **13a/b** containing the nematic liquid crystal material **14a/b**.

[0024] An alternate liquid crystal thermo-optic switch architecture **50** is shown in FIG. 4. In this alternate switch architecture **50**, one of the trenches **51** is filled with a fixed index material **52**. The refractive index of this material **52** is made to be higher than the liquid crystal material's **14** ordinary index but lower than its isotropic index. The differential refractive index loading of the Y-branch **11** can therefore be effected through the control of the temperature of just the single liquid crystal filled trench **13**. Furthermore, this switch architecture **50** can be operated as a half-latch since the liquid crystal material **14** can be chosen so that it is in its nematic phase at ambient temperatures. In this case, when the liquid crystal filled

trench **13** is at any temperature less than a few degrees below the clearing temperature, the guided mode **16** will remain switched into the output arm **19a** that is adjacent to the trench **51** which contains the fixed index material **52**. In FIG. 4, the liquid crystal material **14** in the lower trench **13** is depicted as being in its nematic phase so that the guided mode **16** is switched into the upper output arm **19a**.

[0025] By employing a liquid crystal material **14** whose nematic and isotropic refractive indices straddle the refractive index of the cladding medium **12** but which are both still less than the refractive index of the Y-branch core **11**, the alternate switch architecture **50** can be made even simpler: since the fixed index material **52** can then have the same index as the cladding medium **12**, the trench **51** can be eliminated.

[0026] Another alternate switch architecture **60** is shown in FIG. 5. In this switch architecture **60**, the dimensions of the liquid crystal filled trenches **61** are made small enough so that even if either or both of the refractive indices of the liquid crystal material **14** is higher than that of the Y-branch core **11**, the effective indices of the trench regions **62** will still be less than the effective index of the Y-branch **63** region. The refractive index loading of the Y-branch **11** can therefore still be accomplished without causing the guided mode **16** to radiate from the Y-branch **11** even if liquid crystal materials **14** with higher refractive indices than the Y-branch core **11** are employed. This alternate switch architecture **60** allows, for example, fused silica waveguides to be loaded by conventional liquid crystals such as E7™ (available from BDH, Ltd.). For the shallow trenches **61** shown in FIG. 5, alignment coatings **31** are best deposited on the trench floor **64** and/or on the trench ceiling **65**.

[0027] An alternate embodiment of the liquid crystal thermo-optic switch in which the switch is configured to operate as a variable optical attenuator **70** is shown in top view in FIG. 6. This alternate switch **70** is similar to the liquid crystal thermo-optic switch **10** shown in FIGS. 1 and 2 with the exception that instead of controlling the temperature of each liquid crystal filled trench **13** with a single temperature control element **15** (see FIG. 2), a plurality of temperature control

elements **71** are employed to hold the liquid crystal material **14** in individual sections **72** of each trench **13** in either the nematic or isotropic phase. When all sections in one trench **13a/b** are held at the lower temperature while all sections of the other trench **13b/a** are held at the higher temperature, the entire guided mode **16** is directed into output arm **19b/a** of the Y-branch **11** that is adjacent to the trench **13b/a** containing the isotropic liquid crystal material **14b/a**. When some sections of the trenches **13** are held at the alternate temperature, the guided mode **16** is split into two output modes **73a,b**. The splitting ratio is determined by how many and which sections of each trench **13** are held at the alternate temperature. One output arm **19b/a** therefore carries the attenuated mode **73b/a** while the other arm **19a/b** carries the compliment mode **73a/b**. In FIG. 6, three of the four sections **72** of the upper liquid crystal filled trench **13a** are depicted as being held at the higher operating temperature while the reverse situation is depicted for the lower trench **13b** so that most of the energy of the guided mode **16** is directed into the upper output arm **19a**.

[0028] By choosing the number and proper lengths of the individual temperature control elements **71**, relative to the total length of the trench **13**, the amount of attenuation produced by a given temperature control element **71** can be given a desired weighting; such as binary for example (in other words 1/2, or 1/4, or 1/8, etc.) relative to the total attenuation provided by the attenuator **70**.

[0029] An even simpler variable optical attenuator architecture **80** is shown in FIG. 7. In this simpler attenuator architecture **80**, a single liquid crystal filled trench **13** of the same type as those used in switches **10**, **40**, and **50**, and for which the temperature is controlled by a plurality of temperature control elements **71** of the same type as those used in the attenuator **70**, is positioned in proximity with and parallel to a single waveguide core **81**. The liquid crystal material **14** and the waveguide core material **81** are chosen so that the refractive index of the waveguide core material **81** is still higher than the liquid crystal material's **14** ordinary refractive index but is now less than the liquid crystal material's **14** isotropic index. When the guided mode **16** passes by a section **72a** which is held at the lower operating temperature, both polarization states of the mode **16** remain guided since

the liquid crystal material's **14a** ordinary index is less than that of the core **81**. However, when the mode **16** passes by a section **72b** that is held at the higher operating temperature, portions of both polarization states of the mode **16** radiate from the waveguide core **81** into the liquid crystal material **14b** since the isotropic index is higher than the refractive index of the core **81**. Moreover, since both polarization states of the mode **16** experience the same isotropic index of the liquid crystal material **14b**, the energy contained in the radiated optical beams **82** associated with each polarization state are substantially equal and so the amount of attenuation provided by the attenuator **80** is polarization independent. In FIG. 7, the last three segments **72** are depicted as being held at the higher operating temperature so that most of the mode's **16** energy is radiated from the waveguide core creating the strongly attenuated output mode **83**.

[0030] Still another alternate switch architecture **90** is shown in FIG. 8. In this switch architecture **90**, a Mach-Zehnder geometry such as that described in R.C. Alferness, *supra*, is employed as the switch's **90** waveguide structure **91**. When both liquid crystal filled trenches **13** are held at the same temperature, the switch **90** is in the cross state. To drive the switch **90** into the bar state, the two liquid crystal-filled trenches **13** are held at alternate operating temperatures in substantially the same way as is done for the Y-branch-based switch **10**. The dimensions of the switch **90** are chosen so that in conjunction with the differential refractive index loading on the two center waveguides **92a,b** produced by the liquid crystal-filled trenches **13a,b** the differential optical phase shift imparted to the two guided modes **93a,b** is sufficient to direct the recombined output mode **94** into the bar state arm **95a**. In FIG. 8, the switch is depicted as being in the bar state in which the input mode **96** is directed into output arm **95a** as a result of trenches **13a/b** being held at the higher/lower operating temperatures.

[0031] As described above, this invention provides a liquid crystal based thermo-optic switch that is capable of efficiently redirecting optical beams of arbitrary polarization state in a channel waveguide geometry. This invention further provides a configuration for the liquid crystal thermo-optic channel waveguide

switch which allows the switch to be operated as a variable attenuator. Moreover, this type of switch and the associated variable attenuator are suitable for routing and attenuating optical signals carried by single-mode optical fibers over wavelength ranges of interest to the telecommunications industry. This type of switch, as well as the liquid crystal thermo-optic trench elements on which it is based, are also suitable for integration with other silica-on-silicon devices to provide routing, shuttering or attenuation functionality.

[0032] The invention can be practiced with various types of materials. For the waveguide core material, the use of glass, doped with materials such as GeO_2, is contemplated for example. The cladding material can also exemplarily be of glass, with a lighter doping. Examples of the liquid crystal material are nematic type liquid crystals, which include, but are not limited to, E7, E5 and 5CB. For E7, the clearing temperature is 60.5 C, with suitable operating temperatures being about 53 C for the nematic phase and about 63 C for the isotropic phase. For E5, the clearing temperature is 50.5 C, with suitable operating temperatures being about 43 C and about 53 C for the nematic and isotropic phases, respectively. For 5CB, the clearing temperature is 35.3 C, with suitable operating temperatures being about 28 C and about 38 C for the nematic and isotropic phases, respectively. It will be appreciated that the particular combinations of materials selected would be dictated at least in part by the required refractive index relationships. Further, selection of glass for the waveguide material is preferred because of the good optical properties and chemical inertness which characterize this material. However, the use of polymeric materials, with proper channel sealing processes, may also be an option. For reference, the ordinary index of refraction of E7 liquid crystal material in the isotropic phase at 63 C is approximately 1.5350 for 1550 nm wavelength light. For that same light, the ordinary index of refraction of E7 liquid crystal material in the nematic phase at 53 C is approximately 1.5025.

[0033] The above are exemplary modes of carrying out the invention and are not intended to be limiting. It will be apparent to those of ordinary skill in the art that

modifications thereto can be made without departure from the spirit and scope of the invention as set forth in the following claims.